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Tri-generation systems: Energy policies, prime movers, cooling technologies, configurations and operation strategies

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ABSTRACT

The serious energy supply problems along with the conventional resources depletion and the environmental conscience regarding global warming and climate change have urged the need for a complete change in the energy production, supply and consumption patterns. Therefore, the switch towards renewable energy resources including solar, biomass, wind and hydro-power in addition to the development of energy efficient technologies are two key factors to attain a secure and reliable energy sector and to mitigate the global warming problem. Tri-generation is one of the most promising technologies allowing the efficient simultaneous production of heat, coolth and power with potential technical, economic and environmental benefits. This paper provides a comprehensive review of the latest developments in the field of combined cooling, heating and power generation. Recent tri-generation supporting mechanisms, prime movers, cooling technologies, system configurations, fuels and renewable energy resources employed are presented and discussed. As the operation strategy is the critical factor governing the tri-generation system performance, the current work presents the recent strategies developed and implemented to optimize the system performance and improve its overall efficiency. While certain technologies employed in tri-generation systems as internal combustion engines, gas turbines and absorption cooling are well-established and have already found their way to the commercial market, other promising technologies including organic Rankine systems, fuel cells and liquid desiccant cooling, are still in the research and development phase with additional work needed to demonstrate their potential and reach commercialization. Based on the detailed and comprehensive review conducted, a summary with the main conclusions in addition to recommendations for future work are reported.

Contents

Abbreviations: AC, Alternating current; CCHP, Combined cooling, heating and power; CDE, Carbon dioxide emission; CHP, Combined heat and power; CHPA, Combined heat and power association; COP, Coefficient of performance; DC, Direct current; DOE, Department of energy; EDM, Electric demand management; EPA, Environmental protection agency; FEL, Following the electric load; FTL, Following the thermal load; GA, Genetic algorithm; HCCI, Homogeneous charge compression ignition; HETS, Hybrid electric-thermal load operation strategy; HT, High temperature; ICE, Internal combustion engine; ORC, Organic Rankine cycle; PAFC, Phosphoric acid fuel cell; PEFC, Polymer electrolyte fuel cell; PEMFC, Proton exchange membrane fuel cell; PGU, Power generation unit; PVT, Photovoltaic–thermal; SOFC, Solid oxide fuel cell; TDM, Thermal demand management; VAT, Value added tax

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1. Introduction

The population growth and technological advancement exhibited in the last two decades along with the desire for higher life standards and comfort levels have led to an unprecedented increase in the energy consumption worldwide. Fig. 1 shows the increase in the total primary energy consumption by region with an increase from 7140.7 Mtoe in 1980 to about 12875.6 Mtoe in 2010. Asia and Oceania has the largest share in the energy consumed in 2010 with about 37.9% followed by North America with 23.1% and Europe with 16.4% [1]. However, conventional fossil fuels are still dominating the energy sector where the global oil production has increased from 3602.7 Mtoe in 2002 to about 4118.9 Mtoe in 2012 with a respective increase in the global oil energy consumption from 78470 thousand barrels/day to about 89774 thousand barrels/day [2]. The total world energy consumption by fuel is presented in Fig. 2 with oil still the dominant resource with 33.1% of the global energy consumed followed by coal (29.9%) and natural gas (24%) [2]. Renewable energy resources contribution to the overall world energy consumption pattern is still less than 9% with 6.6% of hydro-electric power and less than 2% for all other renewables combined. This heavy reliance on conventional fossil fuels has led to an increase in the global energy-related CO_2 emissions by 1.4% to reach 31.6 Gigatonnes in 2012 with a historic peak exceeding 400 ppm in the atmosphere in May 2013 [3].

In addition, energy uses in buildings, mainly electric power, heating and cooling/refrigeration, contribute to about 20–40% of the overall energy consumption with similar contribution to carbon dioxide emissions in the European Union (EU) and USA [4–6]. The majority of these buildings depend on large central stations or plants to provide their electricity demands employing oil, natural gas or coal as fuel resources [7]. However, the operation of these central stations is usually characterized by high rates of energy losses mainly in the form of waste heat. With additional losses in the electric power transmission through high voltage lines and in the transformers, only 35–45% of the overall energy produced by these stations is delivered to the final user [8]. Thus, the high investment cost and high incremental risks of these stations along with their high energy production environmental footprint and complex design favour the switch to more efficient and compact decentralized energy production systems and facilities. In this context, harnessing the discharged waste heat from power generation systems to fulfil heating and cooling needs has been presented and discussed as a viable solution to improve overall system efficiency and reduce the negative environmental impacts [7].

Combined heat and power generation systems (CHP) allow the simultaneous generation of heat and power in a single energy process. It was shown that the installation of 1 million micro-CHP units, with size range of 1–10 kWe, in the UK residential sector would allow an annual cost reduction of about £176 million on the energy production and the mitigation of 2.1 million tons of CO_2

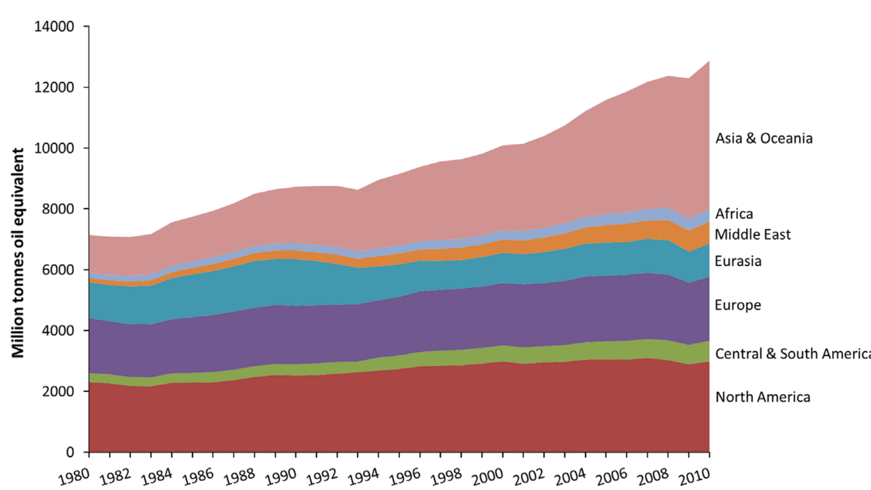


Fig. 1. Total primary energy consumption by region [1].

emissions [9]. Although combined heat and power (CHP), as a proven and reliable technology, provides various technical, economic and environmental advantages compared to the separate production of heat and power, such systems efficiency and capability decrease dramatically in hot climates especially in the summer months where the need for heating is minimal [10]. Thus, a balanced and continuous heat and electricity demand profile all over the year is required to attain high cogeneration system overall efficiency. However, the case is very different in real climatic conditions where many regions exhibit a summer season with an increasing demand for cooling and air conditioning due to larger thermal loads, higher life standards, new buildings design and architectural characteristics and the desire for high levels of thermal comfort [11,12]. If a combined heat and power unit was coupled with a thermally-activated cooling technology, the integrated system is called a combined cooling, heating and power (CCHP) tri-generation system as shown in Fig. 3 [13].

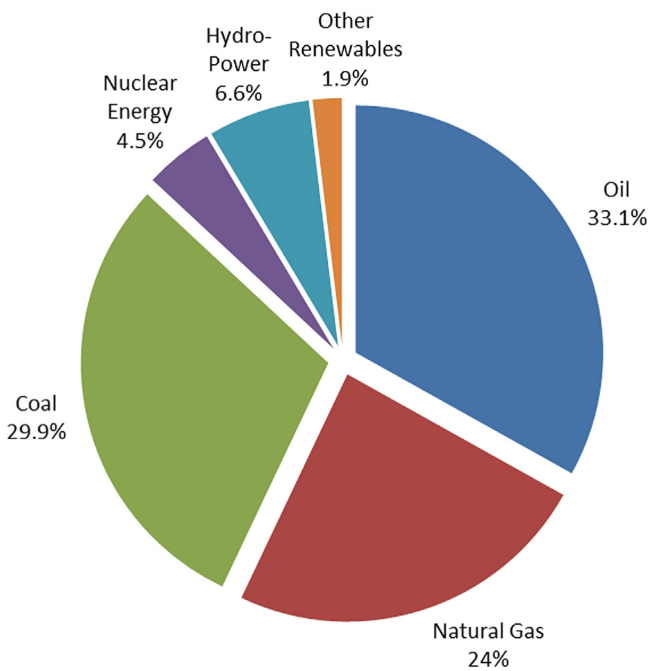


Fig. 2. Total world energy consumption by fuel [2].

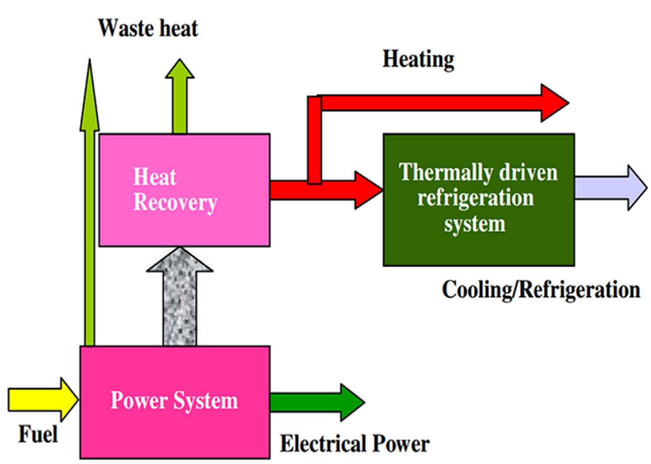


Fig. 3. Schematic of a CCHP tri-generation system [13].

The concept of integrating various units to form a combined heating, cooling and power generation system was first introduced in the early 1980s for municipal cooling and heating [14]. A typical tri-generation system comprises a prime mover, electricity generator, thermally activated technologies, heat recovery unit and a management and control unit. Over the last three decades, tri-generation systems have attracted considerable interest, especially small-scale systems (below 1 MWe), with the development of different options and alternatives for thermally driven cooling technologies and cogeneration units [15–18]. Potential tri-generation users are small and medium-scale applications including multi-residential dwellings and communities, office buildings, hotels, hospitals, commercial and shopping malls, universities, restaurants and food industry [19,20]. Compared to the conventional separate way of energy production (heat by boilers and electric power by central stations) and conventional cogeneration units, tri-generation systems enhance the overall energy production efficiency with various technical, environmental and socio-economic benefits on different levels [21–23] as shown in Fig. 4.

In the first part of this paper, the current status of tri-generation systems is presented with the recent policies and supporting mechanisms to promote the deployment of such systems in different regions. Then, a comprehensive review of the recent tri-generation prime movers, cooling technologies and system configurations is provided along with the fuels utilized and the renewable energy resources employed. Moreover, recent operation strategies developed and implemented to optimize the performance of tri-generation systems are presented and discussed.

2. Tri-generation policies and current status

In addition to the growing body of research and technical developments in the field of tri-generation, measures and policies have been introduced in different countries to promote the deployment of CCHP systems for residential, commercial and industrial applications [24]. A framework for the development of highly efficient combined heat and power generation systems was provided in the European Directive 2004/8/EC in order to attain primary savings in the internal energy market [25]. The total CHP systems capacity installed in the EU in 2010 has exceeded 105 GW where Germany leads with 22% of the EU overall capacity followed by Poland and Denmark with 9%. Moreover, 46% of the electricity generation in Denmark is provided by CHP systems with 30% in Latvia, Finland and Netherlands. On the other hand, the good quality installed CHP capacity has increased from 5614 MWe in 2009 to about 6111 MWe at the end of 2011 with medium-scale CHP systems of capacity ranging between 100 kW and 1 MW dominating the market [26]. Fig. 5 demonstrates the progressive increase in the installed CHP capacity in the UK in the

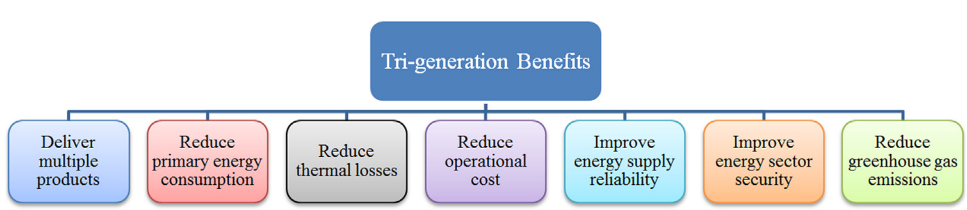


Fig. 4. Tri-generation systems benefits.

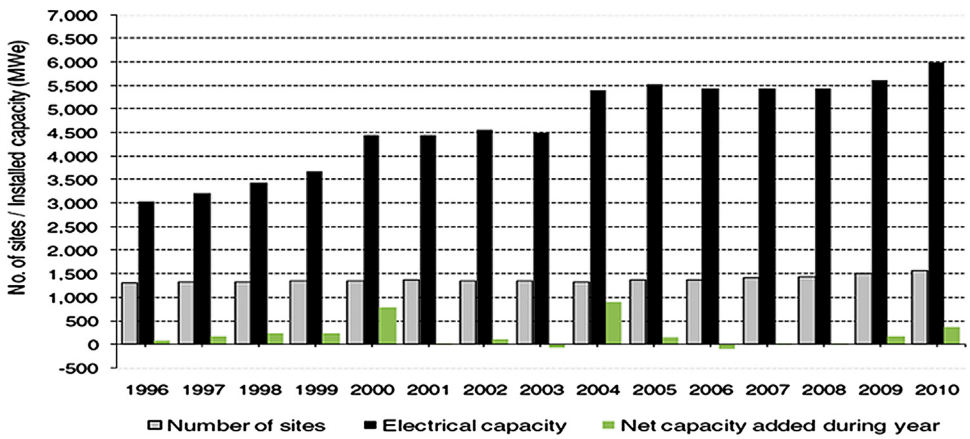


Fig. 5. Installed CHP capacity in the UK [26].

Table 1
Tri-generation systems support mechanisms in the EU countries [28].

Country	Tax support	Feed in tariff	Certificate scheme	Capital grant	Other measures
Austria		✓			✓
Belgium	✓		✓		✓
Bulgaria		✓			✓
Cyprus					✓
Czech Republic		✓			✓
Denmark					
Estonia					✓
Finland				✓	✓
France		✓			✓
Germany		✓			✓
Greece	✓	✓			✓
Hungary		✓			✓
Iceland					✓
Italy	✓	✓		✓	
Latvia		✓			✓
Lithuania		✓			✓
Luxemburg	✓				✓
Malta	✓				✓
Netherlands	✓	✓		✓	✓
Poland			✓		
Portugal				✓	✓
Romania		✓		✓	
Slovakia		✓			
Slovenia		✓			✓
Spain	✓	✓			✓
Sweden				✓	✓
United Kingdom	✓	✓		✓	

recent 15 years. Moreover, 68% of the CHP and CCHP systems installed in UK run on natural gas, where the share of renewable energy-driven systems was only 6% of the total installed capacity in 2010 [26]. In addition, the Government has decreased the VAT from 17.5% to only 5% for buildings to install micro-CHP systems, aiming that by 2050 micro-CHP systems would supply 30–40% of the electricity needs in the UK [27]. Table 1 summarizes the main support mechanisms for the promotion of cogeneration and tri-generation systems in different EU countries based on 2007 situation [28].

The number of CCHP and CHP units installed in Japan by 2006 was about 5190 units in commercial applications with a total capacity of 1715 MW, and 2169 units in industrial applications with 7071 MW as a total capacity, providing 4% of the country's electricity production [29]. The total generation capacity of CCHP systems has increased from about 200 kW in 1986 to exceed 9440 MW in March 2010 [16]. This is due to the measures taken by the Japanese government to promote the development and installation of CCHP systems through special taxation scheme, investment subsidies and low interest loans [30]. The New National Energy Strategy, adopted in 2006, is one of these energy policies aiming to increase the energy consumption efficiency by 30% by 2030 through promoting technology development and commercialization of micro-CHP systems [29].

In the early 1990s, the Chinese government introduced a series of policies including tax exemption and direct subsidies for energy saving projects including CCHP systems [17]. The National Energy Conservation Law set in 1998 has promoted the development of energy efficient technologies all across China where the capacity of CCHP systems, including CHP units, has reached about 28.15 MW. In 2001, the government has put in practice the regulation of CHP to promote the management and development of CHP and CCHP systems leading to an increase in the overall installed capacity, with a 49.6 MW CCHP system installed in Jinan and 120 MW system installed in Hangzhou [31].

The installed CCHP capacity in the United States has increased from about 12 GW in 1980 to 45 GW in 1995 [32]. The US Department of Energy (DOE), the Environmental Protection Agency (EPA) and the Combined Heat and Power Association (CHPA) have launched the "CHP Challenge" in 1998 to increase the installed capacity of CCHP systems to 92 GW in 2010. An objective was set to install CCHP units in 25% of new constructions and 10% of the existing commercial and institutional buildings in 2010. The total installed CCHP electricity capacity in the US has reached about 80 GW in 2004 [33]. However, the overall installed CCHP and CHP capacity in August 2012 represented only 8% of the US generation capacity. Therefore, a challenge has been supported by the President Administration to install 40 GW of new, cost-effective CHP and CCHP by 2020 [34].

In addition, different measures and policies were introduced and implemented in various countries to promote the deployment of CHP and CCHP systems including Russia, Brazil, Iran, India, Mexico and South Africa [35–37]. Recently, the developments in the field of tri-generation have concentrated on improving the design and efficiency of the power generation unit, the thermally-driven cooling technology, the heat recovery unit and the management and control strategy as presented in the following sections.

3. Tri-generation prime movers

Different heat and power generating technologies have been considered in the literature to serve as prime movers for CCHP applications [38]. These technologies could be divided into two categories, combustion-based technologies (Stirling engine, gas turbines, Rankine cycle unit and reciprocating engine) and

Table 2
Assessment and comparison of different tri-generation prime movers [17,40–42].

Tri-generation prime mover	Reciprocating engines	Gas turbines	Stirling engines	Fuel cells	Rankine engines
Advantages	Efficient part load performance	Compact and flexible design	Low noise and emission levels	High electrical efficiency	High flexibility and simple design
	High flexibility	Low maintenance levels	Suitable for domestic applications	Low operation noise and emission levels	Low operational pressure and temperature
	Short start-up time required	Moderate output heat temperature	Possibility to run by renewables	High output temperature	Wide range of fuels utilized
Disadvantages	Large number of moving parts	Inefficient part load performance	Require long start-up time	Very high capital and investment costs	Relatively low electrical efficiency
	High mechanical vibration and noise levels	Unsuitable for intermittent use and frequent start/stop applications	High investment costs	Efficient hydrogen storage techniques are required	More research and commercial development needed in ORC field
	High emission rates		Limited adaptability variable output	Complex design	
Capacity	up to 75 MW	up to 250 MW	up to 55 kW	up to 2 MW	up to 250 MW
Electrical efficiency	25–45%	18–36%	15–35%	37–60%	15–38%
Overall efficiency	65–80%	65%-75%	60–80%	55–80%	80%
Lifetime (h)	20000–50000	5000–40000	10000–30000	10000–65000	30000–50000
Fuels used	Diesel, natural gas, propane, biogas, landfill gas	Propane, natural gas, distillate oil, biogas	Any Fuel including natural gas and bio-fuels	Hydrogen, methanol, natural gas, propane	Any Fuel including natural gas and bio-fuels
Electrical to thermal ratio	0.5–1	0.4–0.7	0.15–0.4	0.5–2	0.15–0.4
Waste heat temperature (°C)	80–200	120–350	up to 85	up to 1000	up to 100
Thermal output (kJ/kWh)	3376–5908	3376–7174	-	1900–4431	1065–52753
Part load efficiency	High	Low	Moderate	Very High	Moderate
Start-up time	>10 s	>10 min	-	>3 h	>1 h
Footprint (sqft/kWe)	0.062–0.47	0.18–0.42	3–6.5	0.5–2	<0.1
Noise level	High	Moderate	Moderate	Low	Moderate
Investment costs ($/kWe)	340–1600	450–1500	1300–2000	2500–3500	1000–2000
NO_x emissions (kg/MWh)	up to 10	0.1–0.5	0.23	0.005–0.01	(fuel-dependent)
CO_2 emissions (kg/MWh)	up to 650	580–720	672	430–490	(fuel-dependent)

electrochemical-based technologies (fuel cells) [39]. Some of these technologies are commercially mature including reciprocating engines and gas turbines with wide availability in the market, while others are still in the research and development stage with limited commercial systems finding their way to the market including Stirling-based units, organic Rankine cycle (ORC) based-systems and fuel cell-driven units. Table 2 presents a comparison and assessment of the main prime movers listing their major advantages and disadvantages when employed in CCHP tri-generation applications.

3.1. Internal combustion engines

Due to their flat efficiency curve above 30% and relatively high electrical power output and limited initial investment cost, reciprocating internal combustion engines (ICE) are the most commonly used prime mover for medium-scale (100–5000 kW) CHP and CCHP applications [43]. ICE is a mature and proven technology and can be classified into two main types, compression ignition and spark ignition engines. Reciprocating engines can be fuelled by diesel oil, natural gas or gasoline, and they are more suited for large-scale applications [44]. Waste heat from ICE can be recovered at different levels, from exhaust gases (at 200–400 °C) and from jacket water cooling and oil cooling (at 90–125 °C) [45]. Generally, reciprocating micro-CHP systems have a total (thermal and electrical) efficiency of about 80% [46]. However, reciprocating engine systems are very noisy and need frequent maintenance in addition to the high level of nitrogen oxides emissions which make them unattractive for small residential applications [27].

A large number of studies have been presented in the literature investigating different aspects related to ICE-based tri-generation systems both theoretically and experimentally. Balli et al. [47] conducted a thermodynamic and thermo-economic analysis of a tri-generation system using a 6.5 MW diesel engine. Wang et al. [7] studied the performance of a mini-scale tri-generation system employing a hydrogen-fuelled diesel engine and an absorption cooling unit. It was shown that the overall efficiency of the system in the combined heating and power mode is higher than that of the tri-generation mode. Parise et al. [48] investigated a biofuel-driven CCHP system using a compression ignition ICE coupled with an electric vapour compression heat pump and an auxiliary boiler. They reported a reduction of 50% on primary energy and 95% on CO_2 emissions. In addition, a combined configuration of an ICE-based tri-generation system and a reversible heat pump was proposed in [49,50]. Moran et al. [51] simulated the performance of a CCHP system with an ICE running on natural gas and diesel. Another study was conducted by Maidment et al. [52] to investigate the feasibility of integrating a combustion engine with an absorption chiller for a supermarket application. Tracy et al. [53] analysed the performance of a small-scale ICE-driven CCHP system based on the first and second law of thermodynamics. Zhao et al. [54] studied the feasibility of recovering the ICE exhaust gas heat to drive an absorption heat pump and cooling water heat for space heating. Moreover, Temir et al. [55] conducted an exergoeconomic study of a tri-generation system with reciprocating ICE, absorption chiller and waste heat boiler. Another economic and exergetic analysis of a CCHP system using a micro-ICE was presented by Huangfu et al. [56], and they indicated that the electrical efficiency of the ICE unit should be improved. In another study, the authors presented an experimental study of a CCHP system for building applications employing an ICE of 12 kW electricity output and an adsorption chiller with 9 kW cooling capacity [57].

In addition, Cardona et al. [58,59] carried out a design optimization for a tri-generation system for civil buildings with an Otto-cycle reciprocating engine, lithium bromide–water absorption chiller and auxiliary electric chiller and gas-fuelled boiler. Two different operational strategies for an ICE-based tri-generation system were discussed and compared by Santo [60]. He reported an energy utilization factor between 65% and 81% with an exergy efficiency between 35% and 38.4%. Another hybrid tri-generation system was proposed by Li et al. [61] employing internal combustion engine and LiBr absorption chiller and running with solar energy and methanol. The overall energy efficiency of the system ranges between 40% and 50% in summer and 38% and 47% in winter. Marimon et al. [62] investigated the possibility of integrating an ICE-based tri-generation system with an indirect refrigeration cascade compression system in a supermarket in Barcelona, and less than 6 years payback period was reported. Huang et al. [63] proposed a tri-generation system consisting of an ICE integrated with a biomass gasification unit shown in Fig. 6. Gas produced by the gasification unit is introduced to the engine to produce electricity where the waste heat is recovered to provide heating needs and cooling power through an absorption cooling unit. The specific investment of the tri-generation system was shown to be very high ranging between £2520/kWe and £2579/kWe.

Few experimental investigations have been presented in the literature for ICE-based tri-generation systems. A laboratory testing

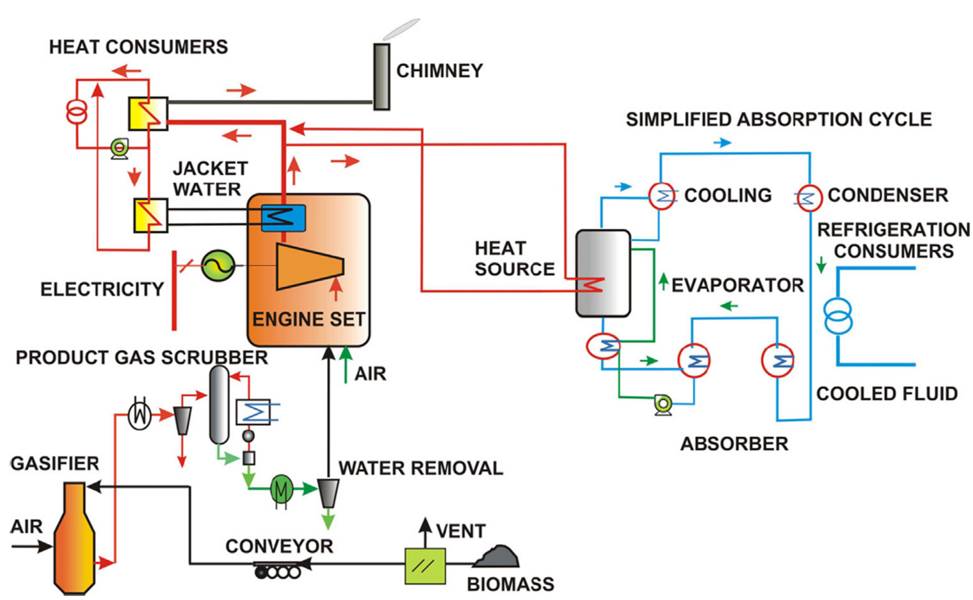


Fig. 6. ICE-based tri-generation system with a biomass gasification unit [63].

was conducted by Fu et al. [64] for a tri-generation system consisting of a 70-kW natural gas-fired ICE with various heat recovery units in addition to a liquid desiccant dehumidification system and a double-effect absorption heat pump. It was shown that the system overall efficiency can reach 90% at peak operating conditions in winter. Another tri-generation system using a natural gas-fired ICE and a liquid LiCl–water desiccant cooling system was proposed and analysed by Badami et al. [65] and a payback period of 6.8–7.6 years was reported. Angrisani et al. [12] conducted an experimental study of a micro-CCHP system using natural gas-fuelled reciprocating ICE coupled with a thermal–chemical absorption cooling unit. It was shown that the system produces 5.4 kWe allowing a reduction of 26% on CO_2 emissions and 30% on the operating cost. Godefroy et al. [66,67] presented an experimental and theoretical analysis of a small-scale CCHP system using a 5.5 kWe gas engine and an ejector cooling unit. They reported a 15% fuel savings compared to the conventional separate production. Kong et al. [68] conducted an energetic analysis and an experimental study of the performance of micro-CCHP system using a natural gas engine and a new absorption chiller. Another experimental investigation was presented by Lin et al. [69] to study the performance of a micro-scale residential CCHP using a diesel engine as a prime mover. Compared to a power-only generation plant, they reported an increase in the thermal efficiency between 2 and 4.4 times. A similar experimental study of a micro-CCHP system with a compression ignition diesel engine and an absorption refrigeration unit was performed by Khatri et al. [70]. It was shown that the system total thermal efficiency is 86.2% at full load compared to 33.7% for separate generation, with 60.71% reduction on the CO_2 emissions.

3.2. Gas turbines

Gas turbine combined heat and power system consists generally of a generator, combustion chamber, recuperator, compressor and turbine connected by a shaft [45]. Heat from the system is recovered from the hot exhaust gas using a heat recovery system. Gas turbine systems of size ranging from several hundred kilowatts to several hundred megawatts are widely available serving different commercial and industrial applications. Recently, micro-turbines have been developed with the size ranging from 30 to 400 kW to serve small-scale applications [16]. Using the regenerative Brayton cycle and high-speed centrifugal turbo machines, such systems are considered nowadays as potential alternative to the conventional ICE especially for mini-scale systems [45]. Compared to ICE-based systems, gas turbines are more compact and require less maintenance, with hot gases released at a temperature of 250 °C that could easily drive thermally-activated cooling technologies [71]. However, micro-turbine applications in the residential and building sector are still very limited due to

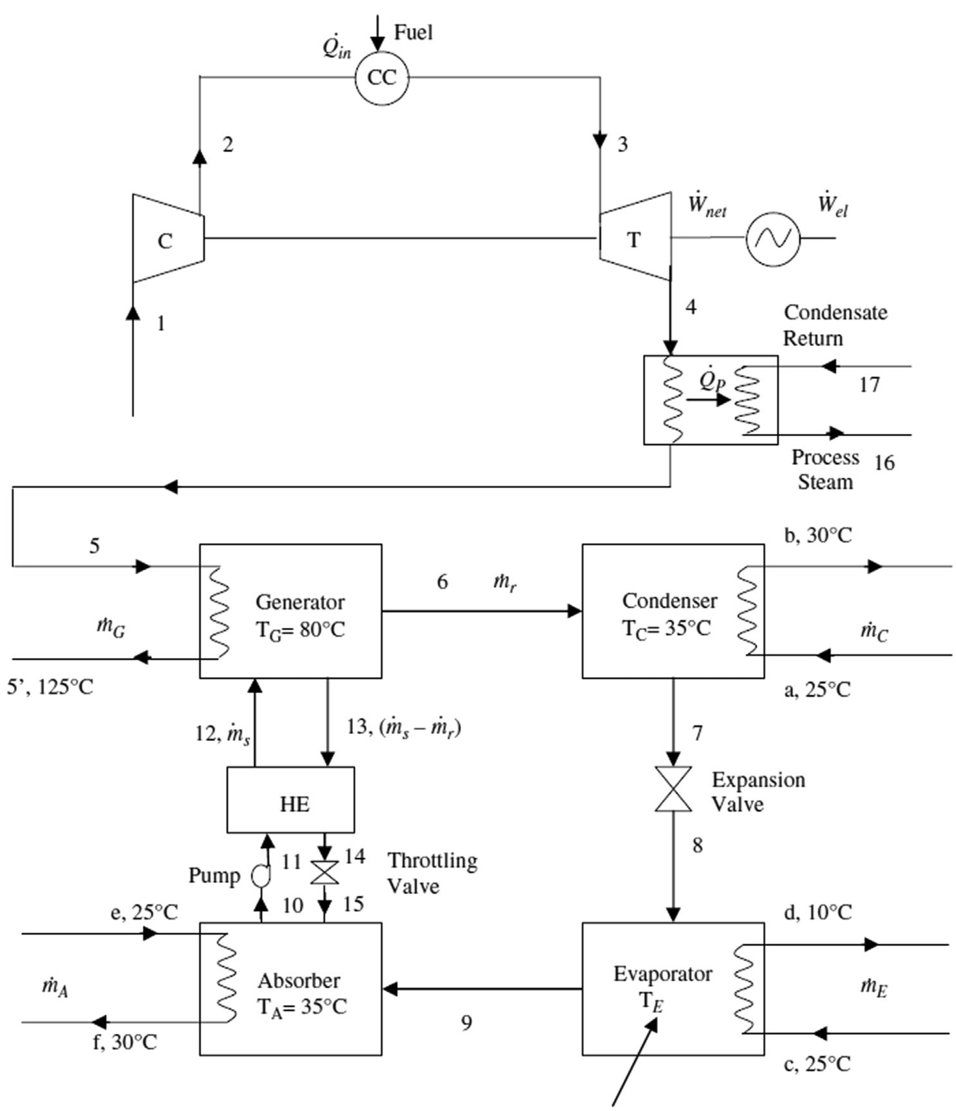


Fig. 7. Tri-generation system with a gas turbine and absorption cooling cycle [76].

their low electrical efficiency and inflexibility to load profile changes.

Many studies have been presented in the literature employing gas turbines as prime movers for CCHP systems, with different sizes and various configurations. Calva et al. [72] presented a simple energy model to design and evaluate different gas turbine configurations for tri-generation plants. Huicochea et al. [73] presented a thermodynamic modelling of a tri-generation system consisting of a micro-gas turbine of 28 kW as a prime mover coupled to a double effect absorption chiller. Another tri-generation system consisting of a micro-gas turbine, a steam ejector refrigeration unit and heat recovery steam generator was studied and discussed by Ameri et al. [74]. A thermodynamic analysis was carried out and they reported a considerable reduction in the primary energy consumption in summer and winter compared to conventional separate production systems. A thermodynamic analysis to optimize the energetic performance of a gas turbine-based tri-generation system was performed by Minciuc et al. [75].

A number of studies have investigated the effect of different gas turbine CCHP parameters on the overall performance. Khaliq et al. [76,77] investigated the effect of the turbine inlet temperature, process heat pressure, compressor pressure ratio, pressure drop in combustor and evaporator temperature on the performance of a tri-generation system with a gas turbine cycle as shown in Fig. 7. They reported that the combustion and steam generation process contributes to more than 80% of the overall exergy destruction in the CCHP plant. Martins et al. [78] evaluated the thermodynamic performance of a tri-generation system with a gas turbine and water–NH_3 absorption cooling unit. They reported a total thermal efficiency of 82% with 0.48 absorption chiller COP for the optimized case with the compressor compression ratio and the turbine expansion ratio as the most influential parameters in the tri-generation system. Ghaebi et al. [79] carried out energy, exergy and thermo-economic analysis of a CCHP system with a gas turbine, heat recovery steam generator and an absorption chiller. They reported an increase in the system energy and exergy efficiency but with an increase in the overall system cost. A tri-generation system using a gas turbine with 100 MW power, 70 MW heat and 9 MW cooling capacity have been studied by Salehzadeh et al. [80] investigating the effect of various parameters on the system performance.

In addition, Ehyaei et al. [81] conducted a complete energetic, economic and environmental analysis of a CCHP system using a micro-gas turbine to provide heating, cooling and electric power for a 10-storey residential building in Tehran, and a high system initial investment cost was reported. Hwang [82] conducted an energetic and economic study to investigate the potential of coupling a micro-turbine with an absorption chiller. Another economic study was presented by Ziher et al. [83] to investigate the performance of a gas turbine-based tri-generation plant in a hospital. They recommended coupling the gas turbine CHP unit with a steam absorption and compression chillers employing a cold storage system. A linear programming model to optimize the CCHP system performance and reduce the overall cost was presented by Kong et al. [84]. A tri-generation system consisting of a gas turbine, absorption cooling chiller and heat recovery boiler was considered, and they reported that the electric to gas cost ratio is inversely proportional to the tri-generation system performance. To provide better and accurate prediction for the performance of micro-turbines in CCHP systems, different algorithms have been developed by Labinov et al. [85]. Ge et al. [86] utilized an 80 kW micro-gas turbine in a tri-generation system where 10% of the exhaust gas is recovered by a 12 kW water–ammonia absorption chiller generator. Sun et al. [87] harnessed the exhaust gas of a 24.5 kW micro-gas turbine in addition to an auxiliary burner to operate a double-effect absorption chiller of 52.7 kW cooling capacity. Invernizzi [88] investigated a tri-generation system with a micro-gas turbine and a vapour jet refrigeration system. In addition, Fairchild et al. [89] investigated theoretically and experimentally a cooling, heating and power generation system for buildings. Preter et al. [90] conducted an experimental study for a tri-generation system using a 30 kWe micro-turbine and a direct-fired absorption chiller. Cooling water was produced through recovering waste heat and an overall primary energy utilization factor of 70% was reported.

3.3. Steam and organic Rankine units

Rankine engines convert heat into useful work based on the thermodynamic Rankine cycle. Rankine systems are divided mainly into two categories: steam Rankine systems with water as the working fluid and organic Rankine systems using organic working fluids [91]. Due to their durability, cost effectiveness, lower operational temperature and pressure, high levels of safety and simplicity, CHP and CCHP systems with organic Rankine cycle (ORC) have received increasing attention recently especially for domestic and buildings applications [92]. In addition, such systems offer the possibility of utilizing heat from low-temperature sources as biomass combustion, waste heat and solar energy.

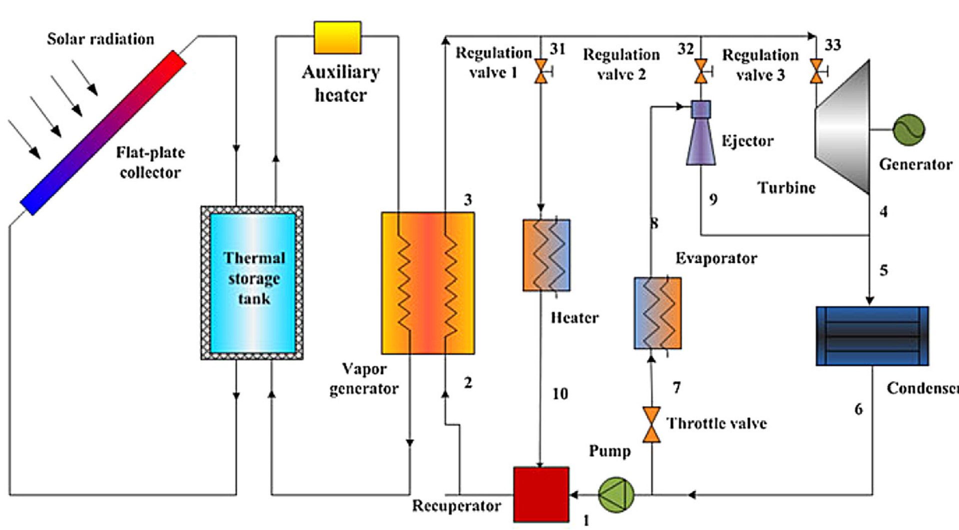


Fig. 8. ORC-based building cooling, heating and power system [99].

ORC-driven CCHP systems are still in the phase of study and development and many companies are working on the development of commercial systems with net power below 200 kWe, including Bosch KWK Systeme GmbH, Freepower, Genlec and Infinity Turbine LLC [93].

Ebrahimi et al. [94] presented an energy and exergy analysis of a micro-CCHP system for a residential application using a micro-scale steam turbine as a prime mover with a steam ejector refrigeration unit to meet the cooling demands. Based on the optimization process, system overall efficiency of 22.82% in summer and 62.15% in winter was reported with a fuel energy saving ratio of 69% and 25% respectively. Lian et al. [95] conducted a thermo-economic analysis of a biomass-driven tri-generation system using a steam turbine as a prime mover coupled with an absorption chiller. It was found that the overall production cost is directly proportional to steam temperature and inversely proportional to steam pressure, where the furnace accounts for 60% of the overall exergy destruction. Khaliq et al. [77] proposed a waste heat recovery-based tri-generation system consisting of a heat recovery steam generator, Rankine power cycle and absorption cooling unit. An energy and exergy analysis was carried out and a decrease in the energy and exergy efficiencies was reported with the increase in the ambient air temperature. It was shown that the exergy efficiency is directly proportional to the process heat pressure where the energy efficiency is directly proportional to the exhaust gas temperature.

Moreover, Wang et al. [96,97] investigated the use of a waste heat source to drive an ORC-based CHP system integrated with a vapour compression cooling unit and a maximum CCHP system COP of 0.66 was reported. Huang et al. [98] carried out modelling, simulation and techno-economic analysis of a small scale biomass-driven tri-generation system using an organic Rankine unit and an absorption cooling system. The maximum efficiency reported was 11.1% for power mode, 85% for combined heat and power mode and 71.7% for tri-generation mode. They recommended a heat to power ratio in the range of 4.5 and 6.7 for the biomass-driven ORC-based CCHP system. Wang et al. [99] proposed a building CCHP system using ORC-based CHP system and an integrated ejector cooling unit as shown in Fig. 8. R245fa was employed as a working fluid and an array of flat-plate solar collectors was used as a heating source. They reported that the combined cooling and power system efficiency is proportional to the turbine inlet temperature, where the combined heating and power system efficiency is inversely proportional to the turbine inlet pressure. The system efficiency reported was 19.1% for the combined heating and power mode, 27.24% for the combined cooling and power mode and 10.47% for the power mode. An exergetic analysis was performed by Al-Sulaiman et al. [100] for an ORC- based tri-generation system with a single-effect absorption chiller, using a parabolic trough solar collector for heat input. Different modes of operation were considered and the maximum electrical–exergy efficiency reported for the solar mode, solar and storage mode and storage mode was 7%, 3.5% and 3% respectively. Similar study was conducted by the authors but using a biomass boiler to drive the ORC-based tri-generation system [101]. They reported a fuel utilization efficiency of 88% for the CCHP unit compared to 12% for separate electrical power production.

3.4. Stirling engine

Stirling engine is initially a reciprocating engine with a closed cylinder where fuel combustion takes place in a separate combustion chamber, and thus it is known as a piston external combustion engine [44]. Stirling CHP systems provide higher flexibility, lower emissions and are quieter in their operation compared to internal combustion systems. However, small scale Stirling CHP systems tend to be more expensive with low electrical efficiencies in the range of 10–15% [27]. Several Stirling CHP units were recently introduced to the market including Sunachine unit of 3 kWe maximum output and the Whispergen 1 kWe unit [39]. Although, Stirling-based systems provide quiet operation with good partial load performance, employing such units in CCHP systems is still in the research and development phase due to the

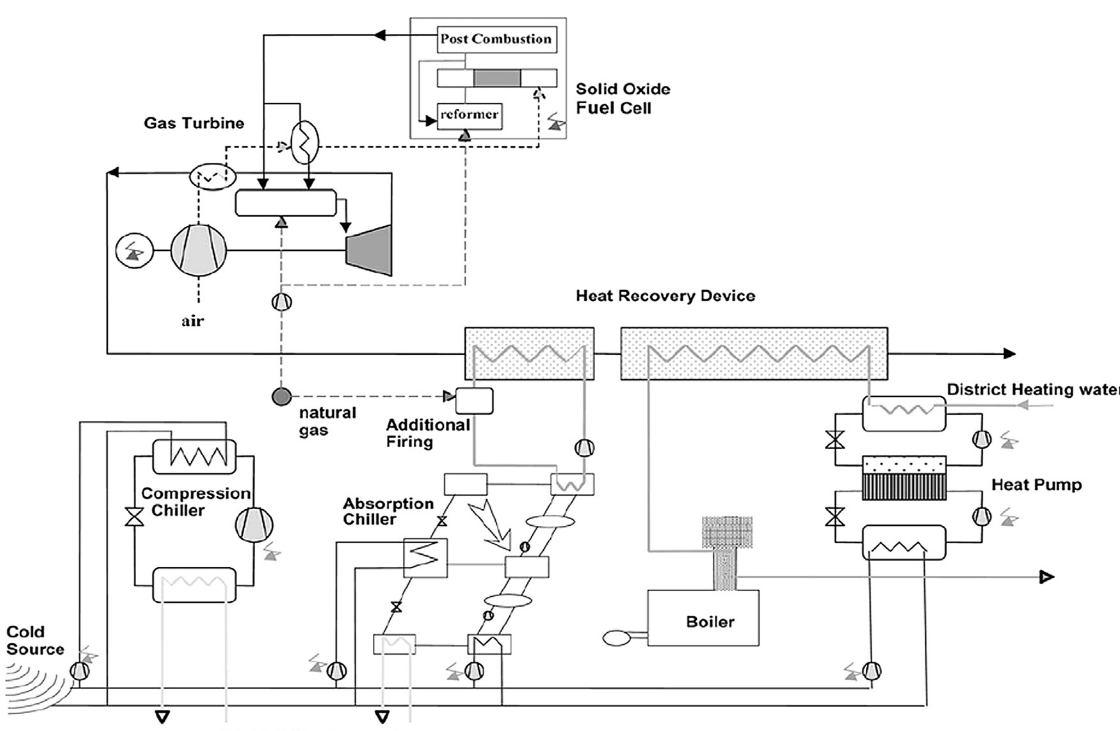


Fig. 9. Gas turbine–SOFC tri-generation system [113].

relatively low power generation efficiency and high investment costs [16,93].

Very few studies have considered and investigated Stirling engines as prime movers for tri-generation systems. Kong et al. [102] performed an energetic and economic analysis to assess the feasibility of employing Stirling engines to provide cooling, heating and power demands in China. A small-scale CCHP system consisting of a Stirling unit and a double effect absorption chiller was studied. They reported 33% primary energy savings in the case of CCHP system compared to conventional separate energy production systems. Harrod et al. [103] investigated the effect of individual tri-generation components, including the prime mover, heat recovery system, auxiliary boiler, absorption chiller, and heating coil, on the overall performance of the system. A design and sizing analysis was carried out using a biomass-fired Stirling engine to provide cooling, heating and power demands for a small office building in Atlanta. They proposed an 8 kW Stirling engine to serve a 511 m^2 area facility. They indicated that the fuel cost has the largest influence on the system operational cost with an increase of 200% when using common fuels as natural gas instead of wood chips to run the Stirling engine.

3.5. Fuel cells

Generally, a fuel cell CHP system consists of a fuel cell stack with cathode, anode and electrolyte, a fuel reformer for fuel preparation and a power conditioner to transform DC to AC electricity. Different types of fuel cells are used for CHP systems depending on the size and nature of the application, including solid oxide fuel cells (SOFC), polymer electrolyte fuel cells (PEFC) and proton exchange membrane fuel cells (PEMFC). PEFC have small dimensions with lower costs compared to other fuel cells but also with lower electrical efficiency [104]. SOFC's operate at very high temperatures up to 1000 °C due to their hard ceramic-based electrolyte. SOFC micro-CHP systems can use natural gas as a fuel and can reach a very high electrical efficiency up to 55%. PEMFC systems have low operating temperatures and they can meet shifts in power demands. In general, fuel cell CHP systems are very quiet and provide high levels of reliability, modularity and rapid adaptability to load changes, but with very high investment costs and complex design compared to other technologies [105]. Lately, several fuel cell micro-CHP units were developed including the 4.6 kWe Vaillant PEMFC unit and the 1 kWe Sulzer Hexis SOFC unit [39], with the phosphoric acid fuel cell (PAFC) as the most widely deployed fuel cell in commercial services especially for stationary power generation [16].

Few research works have been presented considering fuel cell as the main prime mover for tri-generation systems. Henderson et al. [106] used TRNSYS to investigate the viability of integrating a fuel cell unit into space heating and cooling and water heating equipment in buildings. Margalef et al. [107] integrated a molten carbonate fuel cell and absorption chiller to provide cooling, heating and power. Based on the simulations, they proposed integrating a 300 kW commercial molten carbonate fuel cell with an absorption chiller of 40 refrigeration ton capacity. Through mixing the fuel cell exhaust gases with a fraction of the chiller exhaust gas, an overall system efficiency of 71.7% was reported. Bizzarri et al. [108] presented a theoretical analysis of the integration of PAFC grid-connected plants with absorption cooling chillers. A case study of nine hospitals in Italy was considered and the performance of the proposed hybrid system was compared to the existing conventional systems. Although yielding a reduction in the greenhouse gas emissions and primary energy consumption, they indicated that the scenarios proposed were not cost effective.

Solid oxide fuel cells were investigated in different studies as a potential prime mover for tri-generation systems. Weber et al. [109] presented a tri-generation system consisting of a SOFC and two absorption chillers. They reported that the system can reduce

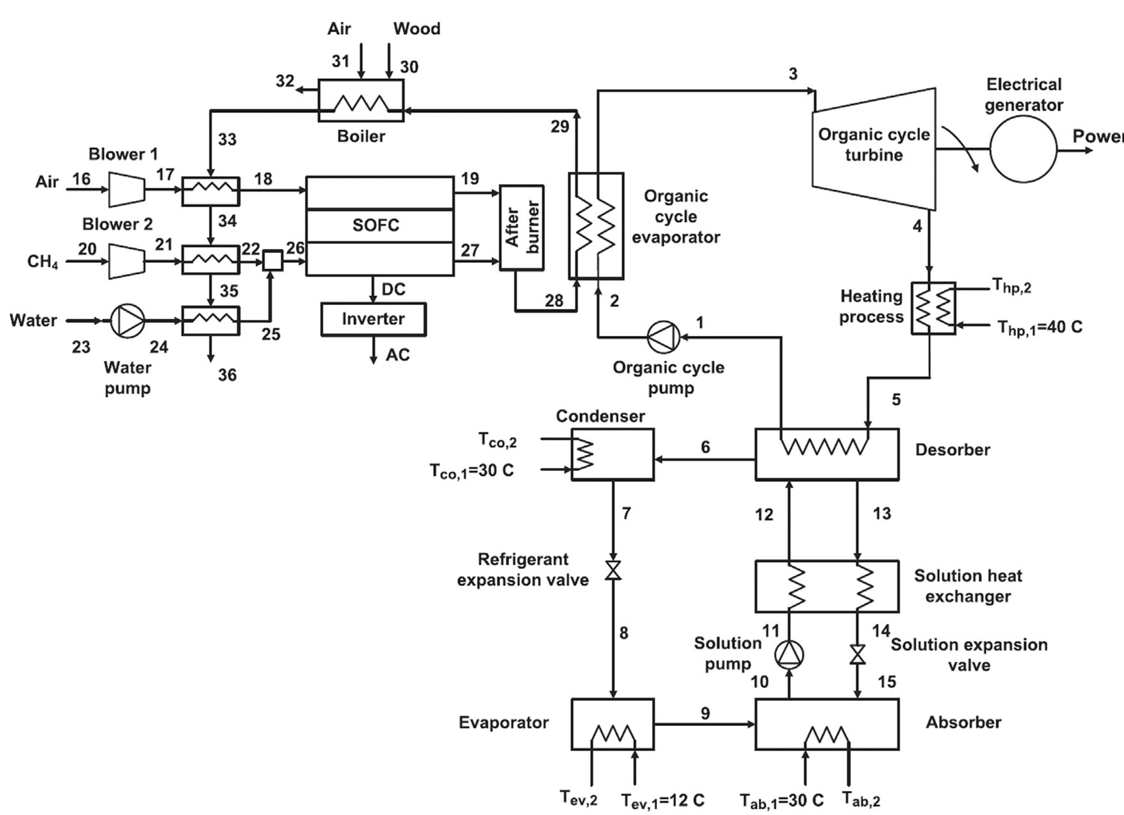


Fig. 10. ORC–SOFC tri-generation system [116].

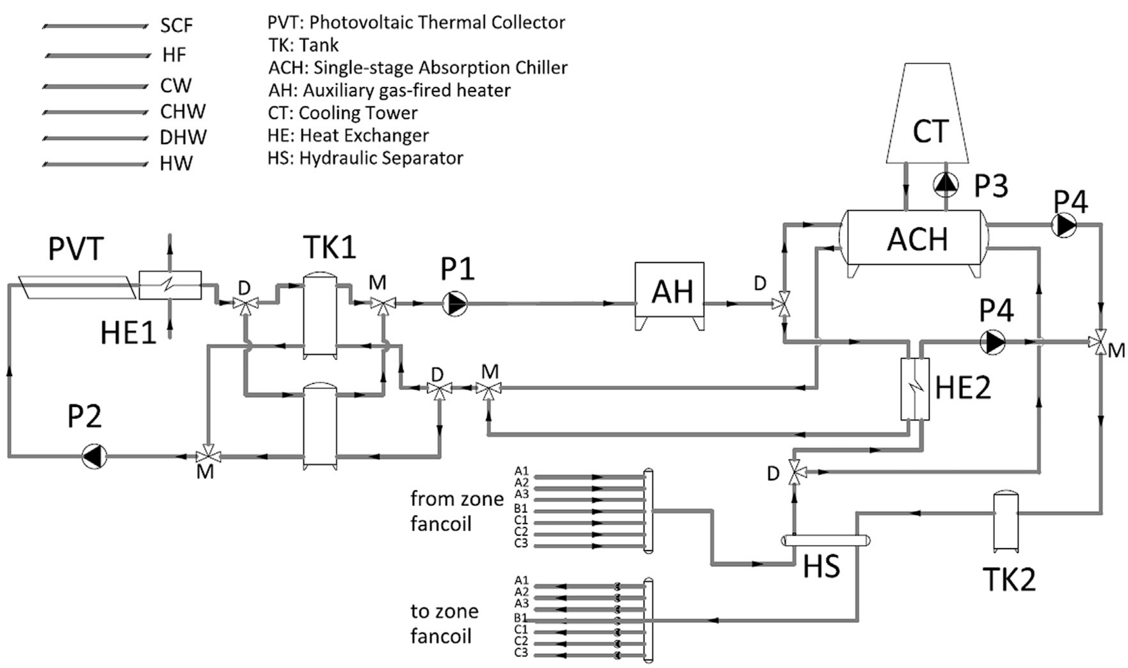


Fig. 11. Tri-generation system with PVT collector and absorption chiller [121].

CO_2 emissions by 45% but with an estimated cost of 290% compared to conventional energy production systems. Zink et al. [110] proposed a tri-generation system based on a SOFC power generation unit with an absorption cooling and heating system. A system efficiency of 87% was reported, and they concluded that such integration could be feasible in the near future with the development and commercialization of fuel cells. Malico et al. [111] presented a similar tri-generation system employing a high temperature SOFC integrated with an absorption chiller and an auxiliary boiler to provide electricity, hot water and heating and cooling needs of a hospital. Based on an investment analysis, they reported that the proposed SOFC-based CCHP system was not financially feasible for such applications. Yu et al. [112] studied a tri-generation system using an internal reforming SOFC and a double effect water–lithium bromide absorption chiller. A parametric study was conducted and the overall efficiency of the proposed CCHP system was above 84%. They reported an increase in the power mode efficiency and the combined cooling and power mode efficiency with the increase in the inlet air temperature.

3.6. Prime movers combinations

Although the majority of the tri-generation works presented in the literature deal with a single prime mover, a number of studies have been presented recently investigating and analysing the performance of tri-generation systems driven by two or more prime movers. This section summarizes the research work carried out integrating different prime movers in various configurations along with the main reported results and findings.

3.6.1. Gas turbine and SOFC

A tri-generation system combining a gas turbine and SOFC with an integrated heat pump was presented by Burer et al. [113] as shown in Fig. 9. The tri-generation system performance was analysed based on the first and second law of thermodynamics and it was shown that the proposed combination provides potential technical, economic and environmental benefits. Velumani et al. [114] studied a tri-generation system combining a micro-turbine and SOFC and reported a 70% thermal efficiency. Another hybrid tri-generation system was presented by Saito et al. [115] combining micro-turbine and SOFC as prime movers with an integrated LiBr–water absorption refrigerator. Energy demand and consumption analysis was performed for different applications and they reported a reduction in the annual fuel consumption by 32%, 36% and 42% for apartments, offices and hotels respectively.

3.6.2. ORC and another prime mover

Al-Sulaiman et al. [116] examined a tri-generation system combining an ORC unit with a SOFC for heating, cooling and power generation as shown in Fig. 10. They reported a tri-generation efficiency of 74%, cooling cogeneration efficiency of 57% and heating cogeneration efficiency of 71%. Ahmadi et al. [117] presented a CCHP system combining a gas turbine and an ORC unit with a single-effect absorption chiller and a domestic water heater. They reported an increase in the system exergy efficiency with the increase in the compressor pressure ratio. The proposed CCHP system allows a reduction in CO_2 emissions compared to micro-gas turbine and CHP cycles.

3.6.3. Solar-driven technologies

Zhai et al. [118] proposed a hybrid CCHP using a parabolic trough solar collector with an evacuated receiver, screw expander and silica gel–water adsorption chiller. Vokas et al. [119] presented a theoretical study of a tri-generation system consisting of a flat plate PVT unit with an adsorption chiller for domestic cooling, heating and power generation. Similar study was conducted by Mittelman et al. [120] employing a concentrating PVT with a single-effect LiBr–water absorption chiller and they reported 19–23% electrical efficiency and 60% thermal efficiency. Another tri-generation system consisting of PVT collectors, single-stage LiBr–H_2O absorption chiller, storage tanks and auxiliary heater was proposed by Calise et al. [121] as shown in Fig. 11. An energetic and economic analysis was performed using a transient simulation model developed with TRNSYS. The dynamic simulation results indicated that the system is capable of providing energy needs all year long with significant energy savings.

3.6.4. Other combinations

Sarabchi et al. [122] proposed a tri-generation system combining a homogeneous charge compression ignition (HCCI) engine, a steam Rankine cycle and a water–ammonia absorption cycle. An optimized system performance is reported providing 28.56% fuel energy savings and 5.19% increase in the exergy efficiency compared to the HCCI standalone operation. A novel metal hydrides-based CCHP system running on solar energy and industrial waste heat was proposed and discussed by Meng et al. [123] in terms of the system configuration and metal hydrides selection. Chua et al. [124] presented a hybrid tri-generation system to provide cooling, heating and power demands of a commercial building. Energetic, economic and environmental analysis was carried out and the optimal CCHP system configuration consists of 80% of micro-turbine, 10% of photovoltaic–thermal and 10% alkaline fuel cell. In another study, Cardona et al. [125] proposed a combination of three gas turbines and two steam turbines to form a basis of a tri-generation system in Malpensa International Airport.

3.7. Prime movers comparison

Many researchers have compared and assessed the performance of tri-generation systems using different prime movers. In addition, different configurations and combinations between prime movers and thermally activated cooling technologies have been examined and discussed from an energetic, exergetic, economic, environmental or integrated point of view. This section summarizes the comparison and assessment works presented in the literature.

3.7.1. ICE and gas turbine

Li et al. [71] compared the performance of CCHP system using an ICE or gas turbine as prime mover. They reported that the ICE-based tri-generation plant provides higher energy saving potential compared to the gas turbine case. Similar comparative study was conducted by Colonna et al. [126], employing a water–ammonia absorption chiller. They reported that the higher electrical efficiency of IEC units is compensated by a higher heat recovery in the case of gas turbine allowing higher refrigeration production. Huang et al. [127] performed an exergoeconomic analysis of a CCHP system using an ICE or micro-turbine as a prime mover. Comparing different system configurations, they indicated that the ICE-based tri-generation system provides less payback period and higher economic-exergy efficiency compared to the gas turbine CCHP. Another exergoeconomic study was conducted by Ziher et al. [128] to compare the performance of a CCHP system with gas turbine or ICE prime mover integrated with compression chiller or single/double effect absorption chiller. It was shown that the ICE and single effect absorption chiller is the most economic option in the period between March and October. Investigating the performance of a tri-generation system for a hospital complex, Arcuri et al. [129] indicated that the ICE option has higher economic feasibility compared to a gas turbine prime mover.

3.7.2. Multiple prime movers

Maraver et al. [130] conducted an environmental analysis of a biomass-driven CCHP system investigating six different configurations and employing Stirling engine or ORC as prime mover with an absorption or adsorption chiller. They concluded that the proposed systems are not viable if the cooling load is too large compared to the heating one. Five tri-generation schemes were presented by Bing et al. [131], investigating different prime movers: Stirling engine, ICE, PAFC and two micro-turbines. They indicated that micro-turbine is the optimal solution where the PAFC option is not economically feasible but provides high energy efficiency with a good reliability level. Similar study was conducted by Mancarella et al. [132] to compare the environmental impact of five different prime movers for a CCHP system, a combined gas-steam turbine, ICE, gas turbine, micro-gas turbine and a combination of fuel cell and gas turbine. Wang et al. [133] compared five different configurations for a tri-generation system employing IEC, Stirling engine, gas turbine, SOFC in addition to a fifth option with electricity supply from the grid. They reported that the ICE-driven CCHP plant provides the best option based on the Chinese government criteria where the SOFC-based system is the most environmentally friendly option.

In addition, a complete energetic, economic and environmental assessment was carried out by Gu et al. [16] investigating different tri-generation prime movers to select the optimal solution for residential buildings in Shanghai. They suggested the selection of gas engine and fuel cell as prime movers from the energy and environmental viewpoints. However, on the economic side, gas engine option is the most favourable solution for residential buildings. Rentizelas et al. [134] compared the performance of an ORC-based tri-generation system and another tri-generation system driven by gasification. They reported that the latter option provides higher electrical efficiency. Kowalski et al. [135] compared the performance of a fuel cell-based CCHP plant with a vapour compression cooling system and a gas turbine-driven CCHP plant using vapour compression and absorption refrigeration unit. Hernandez-Santoyo et al. [136] compared the performance of a gas turbine-based cogeneration plant and a combined gas-steam turbine tri-generation plant, and reported less fuel consumption in the tri-generation case. An analysis of different integration options of prime movers and cooling devices for a micro-scale CCHP system was conducted by Gluesenkamp et al. [137], and they found that micro-turbines, SOFC and HT-PEMFC are promising candidates for tri-generation applications.

3.7.3. Experimental comparison

Badami et al. [138] compared the performance of two natural gas-driven small-scale tri-generation systems forming a part of the cogeneration and tri-generation laboratory at the Politecnico di Torino. The first system has 126, 220, and 210 kW electrical, heating and cooling capacities with an ICE prime mover and a liquid LiCl–water desiccant cooling unit. The second system has 100, 145, and 98 kW electrical, heating and cooling capacities and comprises a micro-turbine coupled with LiBr–water absorption chiller. An energetic and economic analysis was performed for both systems and it was shown that the ICE-based CCHP system provides higher overall energy efficiency. Rocha et al. [139] carried out another experimental investigation of two natural gas-powered small-scale CCHP plants, one using a 30 kW micro-turbine and the other with a 26 kW ICE. The prime movers were coupled with 17.6 kW water–ammonia absorption chiller. They reported a 44.2% primary energy savings for the IEC-based plant compared to only 15.1% for the micro-turbine case.

4. Tri-generation cooling technologies, fuels and renewable resources

4.1. Cooling technologies

Different cooling technologies have been integrated and employed in tri-generation systems to fulfil the cooling and air conditioning demands through heat recovery from the CHP unit prime mover in the form of hot water, steam or exhaust flue gases. These technologies are mainly divided into alternative thermally activated technologies and traditional vapour compression cooling

technologies [140]. Main alternative cooling technologies employed in CCHP tri-generation systems are as follows.

4.1.1. Absorption cooling

Absorption cooling is a mature and well-established cooling technology that has been employed since many years ago in various cooling and air conditioning applications. A simple absorption cycle consists of four main components, an absorber, generator, condenser and evaporator where an absorbent and a refrigerant are employed forming a working pair. Unlike conventional vapour compression systems, absorption systems use heat, supplied at the generator level, to compress the refrigerant vapour instead of a rotating device or compressor. The most common working pairs used in absorption cooling and refrigeration systems are lithium bromide–water and water–ammonia. Absorption cooling systems are classified into single effect, double effect and triple effect systems based on the number of times the heat is utilized within the absorption system. Recently, small-scale single effect absorption cooling systems with a cooling capacity less than 30 kW were introduced in the market including LiBr–H_2O systems: 4.5 kW Rotartica, 4.5 kW Abakus, 10 kW Sonnenklima Suninverse of, 15 kW EAW, 16 kW Broad BCT, 17.5 kW Yazaki WFC-SC5 and H_2O–NH_3 systems: 8 kW AoSol, 12 kW Pink/SolarNext, 17 kW Robur [12,140].

Bruno et al. [141] investigated the integration of different commercially available absorption systems with a biogas-driven micro-turbine. A case study for a sewage treatment plant was considered, and the best configuration reported allows fulfilling the plant heating demands using biogas and natural gas. The authors [142] have also compared the performance of four different micro-gas turbines when coupled with a double effect LiBr–H_2O absorption chiller, concentrating on the effect of natural gas post-combustion on the chiller cooling capacity. Longo et al. [143] investigated the performance of a CCHP system employing a single effect LiBr–H_2O cycle with heat recovery from engine cooling jacket, and a double-effect LiBr–H_2O cycle recovering heat from the engine exhaust. Tassou et al. [144] indicated that the increase in the absorption cooling system COP allows reducing the payback period from 4.5 to 3 years with about1.2 t reduction in the CO_2 emissions.

4.1.2. Adsorption cooling

Adsorption cooling technology is another option to meet the cooling demands within a CCHP tri-generation system. Although adsorption cooling is not as developed as the absorption technology, a number of studies recently have investigated the possibility of coupling a CHP unit with an adsorption cooling unit to provide heating, cooling and power generation needs for various applications [57,145,146]. Simple adsorption cycle consists of one or more adsorber beds, condenser and evaporator. As absorption systems, adsorption cooling units rely on heat supplied at the adsorber level to provide the compression effect with no mechanical compression devices or other moving parts. The most common working pairs used in adsorption cooling units are silica gel–water, zeolite–water and activated carbon–methanol. A number of small-scale adsorption cooling units of less than 15 kW cooling capacity have been developed and introduced in the market recently including the 2.5 kW KWECN, 10 kW SJTU, 7 and 10 kW Invensor, 8 and 15 kW SorTech [12,147,148].

4.1.3. Desiccant cooling

Desiccant dehumidification and cooling is another alternative technology to vapour compression systems that can operate as a standalone system or coupled to another cooling technology including evaporative cooling or other conventional cooling technologies

Table 3
Tri-generation cooling technologies main features [17,66,140,149,154].

Cooling technology	Heat input	Cooling output	COP	Applications
Absorption LiBr–water (single effect)	Steam 2–3 bar, hot water 70–90 °C	Chilled water 5–10 °C	~ 0.7	Large scale CCHP systems for industrial and commercial cooling applications, district cooling, cooling for commercial and residential buildings
LiBr–water (double effect)	Steam 4–8 bar, hot water 120–170 °C	Chilled water 5–10 °C	~ 1.2	
LiBr–water (triple effect)	Hot water 200–230 °C	Chilled water 5–10 °C	1.4–1.5	
Absorption water–NH_3 (single effect)	Steam 2–16 bar, hot water 80–200 °C	Glycol water < 0 °C	~ 0.5	Suitable for cooling applications in food and chemical industries, small air-cooled units for residential and light-commercial buildings
Water–NH_3 (double effect)	Steam 8–16 bar, Hot water 170–220 °C	Chilled water 5–10 °C	0.8–1.2	
Adsorption silica gel-water	Hot water 60–85 °C	Chilled water 7–15 °C	0.3–0.7	Small-scale applications in residential and light-commercial buildings
Adsorption activated carbon-methanol	Steam 2–4 bar, hot water 80–120 °C	Glycol water < 0 °C	0.1–0.4	Experimental applications, ice production and refrigeration for commercial applications
Liquid desiccant cooling	Hot water 60–90 °C, hot air 80–110 °C	Dehumidified cold air 18–26 °C	0.5–1.2	Providing thermal comfort and humidity control in residential buildings, drying and dehumidification applications
Solid desiccant cooling	Steam 2–4 bar, hot water 60–150 °C	Dehumidified cold Air 18–26 °C	0.3–1	Providing thermal comfort and humidity control in residential buildings, industrial applications and processes
Ejector cooling	Hot water 70–130 °C	Chilled water 5–15 °C	< 0.8	Applications in food processing factories for product and process cooling and transport refrigeration, small-scale buildings air conditioning applications
Integrated absorption–CO_2 refrigeration cycle	Depends on the absorption unit employed	Brine < 0 °C	5.5–6	Experimental applications, food refrigeration applications

Table 4
Classification of tri-generation research studies by cooling technology and fuel used.

Fuel	Natural gas	Diesel	Biofuels
Cooling technology			
Absorption	Angrisani et al. [12], Chicco et al. [15], Gu et al. [16], Jing et al. [21], Balli et al. [47], Moran et al. [51], Zhao et al. [54], Temir et al. [55], Santo et al. [60], Marimon et al. [62], Fu et al. [64], Li et al. [71], Huicochea et al. [73], Martins et al. [78], Ehyaei et al. [81], Ziher et al. [83], Kong et al. [84], Labinov et al. [85], Fairchild et al. [89], Kong et al. [102], Bizzarri et al. [108], Zink et al. [110], Malico et al. [111], Yu et al. [112], Burer et al. [113], Velumani et al. [114], Ahmadi et al. [117], Sarabchi et al. [122], Chua et al. [124], Colonna et al. [126], Huang et al. [127], Arcuri et al. [129], Kowalski et al. [135], Santoyo et al. [136], Badami et al. [138], Rocha et al. [139], Tassou et al. [144], Suamir et al. [154], Suamir et al. [155], Ahmadi et al. [158], Abdollahi et al. [159], Moya et al. [160], Balli et al. [161], Sugiartha et al. [162], Popli et al. [163], Mago et al. [164], Rosen et al. [165], Maidment et al. [166], Cho et al. [167], Cao et al. [168], Liao et al. [169], Liekens et al. [170], Jaaskelainen et al. [171], Gamou et al. [172], Weber et al. [173], Buck et al. [174], Medrano et al. [175], Li et al. [176], Jing et al. [177]	Balli et al. [47], Moran et al. [51], Lin et al. [69], Khatri et al. [70], Balli et al. [161],	Bruno et al. [141], Liekens et al. [170], Chevalier et al. [178], Costa et al. [179], Gao et al. [180], Wang et al. [181]
Adsorption	Huangfu et al. [56], Huangfu et al. [57], Deng et al. [145], Li et al. [146],		Maraver et al. [93], Maraver et al. [130]
Ejector Cycle	Godefroy et al. [66], Ameri et al. [74], Ebrahimi et al. [94], Wang et al. [99]		
Vapour Compression	Calva et al. [72], Ziher et al. [83], Rosen et al. [165], Piacentino et al. [184]		Parise et al. [48], Chevalier et al. [178]
Liquid Desiccant	Badami et al. [43],Fu et al. [64], Badami et al. [65], Badami et al. [138]		
CO_2 Cycle	Suamir et al. [154], Suamir et al. [155]		
Fuel	Methane/propane	Coal	Methanol
Cooling technology			
Absorption	Khaliq [76], Ghaebi et al. [79], Salehzadeh et al. [80], Sun et al. [87], Saito et al. [115], Ghaebi et al. [182]	Zhang et al. [183]	Li et al. [71]

[149,150]. Desiccant cooling systems are classified into solid desiccant systems and liquid desiccant systems where both are employed mainly to provide thermal comfort and good indoor air quality in buildings through air humidity control and sensible cooling. A solid desiccant system employs a rotary wheel with an integrated desiccant material allowing latent load removal through adsorption. On the other hand, a liquid desiccant system consists of a dehumidifier where air is dehumidified by strong liquid desiccant, and a regenerator to regenerate the weak desiccant solution employing a heat input. Solid desiccant is a more developed technology where liquid desiccant cooling systems are still in the research and development phase with very few products finding their way to the commercial market. Compared to solid desiccants, liquid desiccant-based systems have higher operation flexibility and mobility, lower temperatures for regeneration and lower pressure drop on the air side [151,152].

4.1.4. Other cooling options

In addition to absorption, adsorption and desiccant cooling technologies, ejector cooling is another technology that has been investigated by few researchers as a cooling option within a CCHP tri-generation system [66,74,94,99]. Ejector cooling systems have no moving parts, low fabrication and maintenance costs with the capability to produce refrigeration harnessing a low-temperature (80–85 °C) heat source including waste heat and solar energy [153]. On the other hand, Suamir et al. [154,155] studied theoretically and experimentally the integration of a CO_2 refrigeration cycle with a tri-generation system employing an absorption cooling unit. A supermarket was considered as a case study with an 80 kWe recuperated micro-gas turbine unit and absorption chiller of 50 kW cooling capacity. The refrigeration power generated by the tri-generation system absorption chiller was employed to condense the CO_2 refrigerant in a cascade arrangement. An energy savings up to 30%, greenhouse gas emission savings of 43% and a payback period of 3 years were reported.

The characteristics and features of different cooling technologies employed in tri-generation systems are presented in Table 3 including system heat input, cooling output, COP and specific applications [17,66,140,149,154]. It can be concluded that absorption cooling is the most suitable technology for large-scale applications and industrial refrigeration, where desiccant cooling and dehumidification systems possess a good potential for micro-scale and building applications through providing thermal comfort, humidity control and good indoor air quality.

4.2. Fuels and renewable resources

Table 4 presents a classification of the tri-generation research studies presented in the literature by the fuel used and the cooling technology employed. As shown in Table 4, natural gas is the most commonly used fuel in tri-generation systems throughout the literature. This is due to the gas wide availability, relative low cost and ease of transport. Natural gas tends to be the cleanest burning fossil fuel with no ash or unpleasant odours and low negative environmental impacts. In addition, natural gas can be harnessed and utilized in a wide range of CCHP prime movers including, ICE, gas turbines, steam turbines, fuel cells and Stirling engines [41,42]. Nevertheless, a number of studies have utilized bio-fuels to drive the tri-generation prime movers as an alternative and sustainable fuel produced from renewable feedstock, with much lower greenhouse gas emissions compared to conventional fossil fuels [156]. Being produced domestically, switching to biofuels can reduce the dependence on the unstable foreign fossil fuel supply providing more secure and steady energy supply with less vulnerability to disruptions. Moreover, other primary energy fuels investigated

and utilized in tri-generation studies include diesel, methane, propane, methanol and coal.

On the other hand, it can be concluded from Table 4 that absorption cooling is the dominant technology employed in the tri-generation research as a viable and well-established option integrated with a wide range of prime movers to provide the additional cooling effect desired. Other technologies including adsorption cooling, desiccant cooling and ejector cooling have been investigated by very few researchers and additional work is still needed to assess the feasibility of using such technologies in tri-generation systems.

In addition, different studies have investigated the use of renewable energy resources to provide the heat input required for the CCHP prime mover operation. The most commonly renewable resources employed in the literature are biomass heat, solar energy and fuel cell waste heat as summarized in Table 5. Al-Sulaiman et al. [157] compared the performance of an ORC-based tri-generation system using different renewable energy-based heating resources, a SOFC heat, biomass boiler and solar energy. They reported an exergy efficiency of 38% for the SOFC system, 28% for the biomass system and 18% for the solar-driven tri-generation system. It was shown also that the solar-driven ORC tri-generation system is the best solution based on a thermo-economic and environmental analysis. Maraver et al. [93] analysed six different biomass-driven CCHP system configurations integrating Stirling engine or ORC as prime mover with an absorption or adsorption chiller. They reported that the Stirling engine option might cause ash-related problems when coupled with a biomass source where the ORC option presents higher economic feasibility.

5. Tri-generation system operation strategies

In the design phase of any tri-generation system, certain issues should be taken into account including, system operation strategy, individual units sizing and efficiency, system configuration in addition to the cooling, heating and power load profile of the specific application considered [188]. Regardless of the application and the technologies employed, the operation strategy is the critical factor governing the overall performance of any tri-generation system, where different methods have been implemented in the literature to optimize the system operation depending on the tri-generation technologies utilized [189]. The main aim in selecting the tri-generation system operation strategy is to reduce the system primary energy consumption, operation costs and carbon dioxide emissions. Conventional cogeneration operation strategies, including supplying a constant amount of thermal or electrical energy and operating the system at the maximum capacity for a predetermined period of time, cannot deliver the maximum benefits of tri-generation systems and therefore reduce the system overall efficiency [190]. Thus, new operation strategies have been studied and developed to improve the performance of tri-generation systems and enhance the associated energetic, economic and environmental benefits.

The two most investigated tri-generation operating strategies are: following the thermal load (FTL) and following the electric load (FEL). The two strategies can be described as the thermal demand management (TDM) and the electric demand management (EDM) [191]. When the FTL is implemented, the tri-generation system will fulfil the building's thermal load first, and additional electricity is supplied from the grid if the CCHP yield is not sufficient to meet the electric load. On the other hand, following the electric load operating strategy, the CCHP system will satisfy the building's electric needs first and if the heat produced by the system is not sufficient to meet the thermal load, additional heat is provided by an auxiliary conventional boiler [188]. The tri-generation system attains its peak operating efficiency when both the electric and thermal loads for a specific application are met [192]. The choice between the FTL and the FEL is governed by different factors including the utilized fuel costs, availability of a storage system for excess electricity produced and the ability to sell the electricity to the grid [193].

A non-dimensional analysis of the energy cost and primary energy consumption of a micro-turbine driven tri-generation system was presented by Jalalzadeh-Azar et al. [194]. Two operating strategies were employed and compared, following the electric load (FEL) and following the thermal load (FTL). They reported that the energy consumption in the FTL mode is 11% less than the consumption in FEL mode due to the higher level of waste heat utilization when the FTL strategy is implemented. In addition, the authors reported that employing a micro turbine without a recuperator increase the total primary energy consumption of the system [195]. Mago et al. [164] compared FTL and FEL strategies for ICE-based CCHP system in four different climatic conditions based on the energy consumption, CO_2 emissions and cost, concluding that the FTL yields better performance. In another study, the authors presented an optimized hybrid electric–thermal load operation strategy (HETS) allowing the reduction of energy consumption, cost and CO_2 emissions compared to conventional operation strategies [196]. Smith et al. [197] performed a detailed uncertainty analysis on the simulation predictions of CCHP system performance parameters employing FEL and FTL operating strategies. They reported that implementing the FTL strategy could improve the system performance compared to the FEL operation mode. In addition, Jing et al. [177] carried out a life cycle assessment of a solar building cooling, heating and power system to analyse the performance of the tri-generation system under two

Table 6
Cost, primary energy consumption and carbon dioxide emission for different operation strategies [18].

Case	Cost ($/year)	PEC (kWh/year)	CDE (kg/year)
Reference	448,530	17,817,175	5,829,472
FEL	440,613	15,252,497	2,858,990
FTL with electricity export	436,579	15,299,252	3,557,744
FTL without electricity export	437,407	16,690,110	4,040,238
FSS	440,902	14,984,272	2,914,876

Table 5
Tri-generation studies based on renewable energy resources.

Biomass heat	Solar energy	Fuel cell waste heat
Jing et al. [21], Huang et al. [63], Maraver et al. [93], Lian et al. [95], Huang et al. [98], Al-Sulaiman et al. [101], Harrod et al. [103], Maraver et al. [130], Rentizelas et al. [134], Al-Sulaiman et al. [157], Al-Sulaiman et al. [185], Al-Sulaiman et al. [186]	Li et al. [71], Wang et al. [99], Al-Sulaiman et al. [100], Zhai et al. [118], Vokas et al. [119], Mittelman et al. [120], Calise et al. [121], Meng et al. [123], Chua et al. [124], Al-Sulaiman et al. [157], Buck et al. [174], Medrano et al. [175], Jing et al. [177], Al-Sulaiman et al. [185], Al-Sulaiman et al. [186], Wang et al. [187]	Gu et al. [16], Jing et al. [21], Bizzarri et al. [108], Zink et al. [110], Malico et al. [111], Yu et al. [112], Burer et al. [113], Velumani et al. [114], Saito et al. [115], Al-Sulaiman et al. [116], Chua et al. [124], Kowalski et al. [135], Al-Sulaiman et al. [157], Gamou et al. [172], Weber et al. [173], Al-Sulaiman et al. [185], Al-Sulaiman et al. [186]

operation strategies, FTL and FEL based on the system primary energy consumption (PEC) and the pollution emissions. They reported that the PEC of the system in the FEL mode is higher than that of the FTL mode. However, the FEL strategy provides a more friendly operation mode if the global warming potential and the acidification potential were taken into account.

However, it was reported that both FTL and FEL operation strategies lead to a considerable energy waste [191]. Therefore many researchers have investigated and developed optimized operation strategies for CCHP systems to enhance energy savings and reduce operation costs and emissions [188,198–200]. Mago et al. [18] evaluated the performance of a turbine-driven CCHP system for large office buildings under three different operating strategies, FEL, FTL and following a seasonal strategy (FSS). In the case of FSS, in each month the CCHP system will operate to either FTL or FEL based on the monthly electric- to-thermal load ratio. As shown in Table 6, all the operation strategies studied reduce the operational cost, PEC and CDE compared to the reference case. The proposed FSS strategy allows the largest reduction on the primary energy consumption with 15.9% compared to the reference case. Cardona et al. [201] presented a strategy based on the primary energy savings (PES) and found that the tri-generation system can operate for 2800 h/year at full load increasing the overall thermal energy production. Fumo et al. [202] presented a similar study investigating an operation strategy based on the primary energy savings. In another study [189], the authors proposed an emission operational strategy (ES) to minimize the carbon dioxide emissions from a CCHP system. They compared the system performance under ES and PES strategies and found that the ES allows 5.2% less CO_2 emissions compared to the PES for a CCHP system operating under Minneapolis conditions. A method called "fuel energy savings" was proposed by Li et al. [71] to indicate the ratio of primary energy consumed by the CCHP over the separate production energy consumption. Kavvadias et al. [203] proposed an electrical-equivalent load following operation strategy for CCHP systems and reported that the strategy provides better load coincidence and peak reduction compared to conventional operation strategies.

To identify the CCHP optimal operation mode, Cho et al. [167] developed an energy dispatch algorithm using a linear programming formulation with cooling, heating and electricity loads as constraints. In addition, Santo et al. [60] conducted an energetic and exergetic analysis of an ICE-based CCHP system working under two operational strategies, electrical dispatch mode and full engine load mode. Liu et al. [188] proposed a new operation strategy based on the variational electric cooling to cool ratio in a tri-generation system. The optimal strategy presented is based on the relationship between the power generation unit full capacity output and energy load taking into account the building primary energy consumption and electricity and fuel rates. The proposed operation strategy allows a reduction on the PEC and CED of the tri-generation system compared to the two conventional FEL and FTL strategies. Another optimized CCHP operating strategy was presented by Fang et al. [204] based on the adjustment of the electricity to thermal energy output ratio according to an implemented decision making process. A multi-objective approach was developed by Piacentino et al. [205] to optimize the operation strategy of a tri-generation system based on the cost and emissions reduction taking into account the energy load and price variations on an hourly basis. Moreover, different optimization approaches have been developed to optimize the performance of tri-generation systems and identify the optimal operation strategy including the genetic algorithm optimization [94,206,207], particle swarm optimization algorithm [24,208], linear programming optimization [184,209,210] and mixed integer non-linear programming algorithm [211]. In all these works, the optimization of the cooling, heating and power system performance focuses mainly on three main factors, the system operational costs, primary energy consumption, and carbon dioxide emissions.

6. Conclusion

A comprehensive review of the recent developments in the field of cooling, heating and power generation systems is provided in this paper. The current status of CCHP systems along with the supporting mechanisms and energy policies to promote the deployment of such systems in different regions is presented and discussed. Different CCHP aspects were addressed and examined including prime movers, cooling technologies, fuels, renewable energy resources employed and operating strategies implemented. Based on the detailed literature review conducted, the following conclusions are reported:

1. With the dramatic increase in the world primary energy consumption and the corresponding greenhouse gas emissions, combined cooling, heating and power generation presents a promising technology providing multiple energy products accompanied with highly efficient energy production, greenhouse gas emissions reduction, higher energy supply reliability and lower operational and maintenance costs.
2. Although the installed CHP and CCHP capacity was 105 GW in the EU countries in 2010 and about 82 GW in the USA in 2012, the share of such systems in the overall electricity generation scheme is still relatively low. To promote the deployment of CCHP systems, different countries have developed and implemented energy policies and supporting mechanisms including EU countries, USA, China, Japan, Russia and Brazil. However, major regulatory, market and financial barriers should be overcome including the development of highly efficient and cost-effective small-scale systems, establishment of a technical standard for net metering interconnection and setting guidelines for the role of such distributed energy production systems in the overall energy supply network.
3. Different heat and power generation technologies are considered as prime movers for CCHP applications including internal combustion engines, gas turbines, fuel cells, Rankine cycle-based units and Stirling engines. Internal combustion engines and gas turbines are the two most commonly employed technologies in tri-generation systems to produce heat and electricity where organic Rankine cycle-based units and fuel cells are two promising technologies with additional research needed to demonstrate their potential.
4. Absorption cooling is the dominant thermally activated cooling technology used in tri-generation systems to provide the additional cooling effect. Other options include adsorption cooling, desiccant cooling, ejector cooling and CO_2 refrigeration. Liquid desiccant cooling is a promising technology for tri-generation systems especially for buildings and residential applications, providing thermal comfort and good indoor air quality through air humidity control and sensible cooling.
5. Different fuels have been used to run tri-generation systems including diesel, bio-fuel, methane, coal, but the most commonly utilized fuel is natural gas due to the wide availability, clean burning, relative low cost, ease of transport and low negative environmental impacts. In addition, solar energy, biomass heat and fuel cell waste heat have been harnessed in many research studies to drive tri-generation units and increase the system overall efficiency providing the required heat input.
6. The operation strategy is the key factor for the success of every tri-generation application regardless of the system size,

configuration or the technologies employed. Two major operating strategies have been implemented in the literature: following the thermal load (FTL) and following the electric load (FEL). But due to the energy waste accompanied with the implementation of these two strategies, optimized operation strategies were proposed to improve the CCHP system performance and enhance the overall efficiency.

7. Based on the comprehensive review conducted, key areas for future work and investigation aiming to improve tri-generation systems performance include: development of cost-effective micro-scale tri-generation systems to serve residential and building applications employing fuel cells and ORC units with efficient micro-scale expanders; using CO_2 as a working fluid in the Rankine cycle for heat and power generation in addition to investigating the use of new efficient and environmentally friendly working fluids; integrating thermal and thermo-chemical energy storage units with tri-generation systems to improve the overall efficiency; development of liquid desiccant cooling systems using innovative liquids including ionic solutions; investigating the feasibility of tri-generation system grid-connection using smart grids to increase power generation efficiency and reduce the infrastructure costs.

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